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Developing a new stream metric for comparing stream function using a bank–floodplain sediment budget: a case study of three Piedmont streams

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ABSTRACT: A bank and floodplain sediment budget was created for three Piedmont streams tributary to the Chesapeake Bay. The watersheds of each stream varied in land use from urban (Difficult Run) to urbanizing (Little Conestoga Creek) to agricultural (Linganore Creek). The purpose of the study was to determine the relation between geomorphic parameters and sediment dynamics and to develop a floodplain trapping metric for comparing streams with variable characteristics. Net site sediment budgets were best explained by gradient at Difficult Run, floodplain width at Little Conestoga Creek, and the relation of channel cross-sectional area to floodplain width at Linganore Creek. A correlation for all streams indicated that net site sediment budget was best explained by relative floodplain width (ratio of channel width to floodplain width). A new geomorphic metric, the floodplain trapping factor, was used to compare sediment budgets between streams with differing suspended sediment yields. Site sediment budgets were normalized by floodplain area and divided by the stream's sediment yield to provide a unitless measure of floodplain sediment trapping. A floodplain trapping factor represents the amount of upland sediment that a particular floodplain site can trap (e.g. a factor of 5 would indicate that a particular floodplain site traps the equivalent of 5 times that area in upland erosional source area). Using this factor we determined that Linganore Creek had the highest gross and net (floodplain deposition minus bank erosion) floodplain trapping factor (107 and 46, respectively) that Difficult Run the lowest gross floodplain trapping factor (29) and Little Conestoga Creek had the lowest net floodplain trapping factor (–14, indicating that study sites were net contributors to the suspended sediment load). The trapping factor is a robust metric for comparing three streams of varied watershed and geomorphic character, it promises to be a useful tool for future stream assessments. Published 2012. This article is a U.S. Government work and is in the public domain in the USA.

KEYWORDS: sediment budget; rivers/streams; Chesapeake Bay; legacy sediment; floodplain trapping factor; contingency

Introduction

Suspended sediment has been identified as one of the most detrimental pollutants affecting the Chesapeake Bay ecosystem today (US EPA, 1997, 2006). The highest suspended-sediment concentrations in the Bay watershed occur within streams in the Piedmont physiographic province which is characterized by a landscape of low-relief hills utilized by a mix of urban, agriculture, and forest land uses (Gellis *et al.*, 2009). Stream- and reach-scale sediment budgets, an accounting of the input and export of sediment from a defined system, are regularly used to determine best management practices for stream restoration (Reid *et al.*, 1981; Trimble, 1997). Accurate information on stream-scale sediment budgets, including bank erosion, sediment transport, and channel and floodplain deposition, is rare and notoriously difficult and expensive to gather. Watershed processes that affect a particular stream's sediment budget are complicated by current and historic human alterations to the landscape.

The Piedmont region in the eastern USA has been heavily impacted by historic land uses including land clearing for agriculture, subsequent reforestation in the 20th century, low-head dam construction, and presently by urbanization (Knox, 1972; Pizzuto *et al.*, 2000; Merritts *et al.*, 2011). The effects of colonial-era land clearing on the stream corridor are well documented (Costa, 1975; Jacobson and Coleman, 1986; Walter and Merritts, 2008). Many, if not all, Piedmont floodplains store a significant amount of sediment delivered from upland sources from accelerated erosion during historical land-clearing and subsequent upland erosion (Trimble, 1974; Costa, 1975; Jacobson and Coleman, 1986). This sediment is observed in the field as a distinct fine grained stratigraphic layer of soil referred to as "legacy sediment" that overlies a coarser pre-settlement surface. Legacy sediment is mobilized from the banks and floodplains of streams throughout the mid-Atlantic USA by lateral stream erosion (Meade, 1982; Knox, 2002). The potential for legacy sediment remobilization has probably been exacerbated by a number of historic low-head dams that have retained sediment and are releasing their sediment reservoirs as they fail through time (Walter and Merritts, 2008). Stream entrenchment into legacy sediment has created higher than normal bank heights increasing bank erosion while reducing hydrologic connectivity with the floodplain (Walter and Merritts, 2008). Piedmont floodplains continue to trap sediment during flood events, despite reduced connectivity, but the floodplain sediment flux is probably lower than pre-colonial times (Schenk and Hupp, 2009; Pizzuto *et al.*, 2011).

Piedmont stream sediment loads have also been greatly affected by recent rapid urbanization. The Piedmont physiographic province is developing at the greatest rate of any portion of the Bay watershed while also contributing the highest sediment yield (mass of suspended sediment per unit area of watershed per year, Gellis *et al.*, 2009). The subsequent increase in impervious cover is creating 'flashier' streams; a well-documented hydrologic regime shift towards higher peak discharges over a shorter time caused by the rapid draining of the uplands due to impervious cover (Sauer *et al.*, 1983; Allmendinger *et al.*, 2007). These short, high intensity floods increase the stream power allowing for increased bank erosion and/or channel incision (Booth, 1990). Channel incision, like the impacts of legacy sediment, reduces the hydrologic connectivity with the floodplain by preventing high flows from going overbank (Steiger *et al.*, 1998) and depositing sediment transported during floods on the floodplain (Hupp *et al.*, 2008). Recently urbanized streams experience increased sediment transport (a product of bank erosion or channel incision) resulting from he new hydrologic regime (Morisawa and LaFlure, 1979). Both the increase in sediment transport (increased erosion and/or channel incision), and the potential for reduced floodplain connectivity (decreased sediment trapping), may lead to the high sediment yields observed across the Piedmont province (Gellis *et al.*, 2009).

The present study utilizes a sediment budget constructed using erosion pins to measure bank erosion rates and artificial floodplain marker horizons to monitor floodplain sediment deposition rates. The rates are normalized using bank and floodplain surveys and compared with the geomorphic characteristics of each watershed (described later in Methods). The components of this sediment budget were developed with the understanding that Piedmont streams are impacted by legacy sediment and contemporary land use. Although an intensive and relatively holistic sediment budget extrapolated to the entire stream and watershed is possible through remote sensing (Nelson and Booth, 2002) or intensive monitoring (Hupp *et al.*, 2009), it is not the purpose of this study.

Our objectives are to develop a metric for comparing stream function between basins through the quantification of floodplain and bank sediment storage and supply. A second objective is to use this floodplain–bank sediment budget to better understand the processes that govern sediment within relatively small streams in the Piedmont region of the Chesapeake Bay. This study is focused on three streams in the Piedmont Region (Figure 1), Little Conestoga Creek (LCC, urbanizing watershed), Linganore Creek (LIN, agricultural watershed), and Difficult Run (DR, suburban watershed with a forested riparian zone). A key part of this objective is to understand how well the floodplain functions as a sediment sink at individual sites and streams. The streams are assessed using a site scale bank–floodplain sediment budget

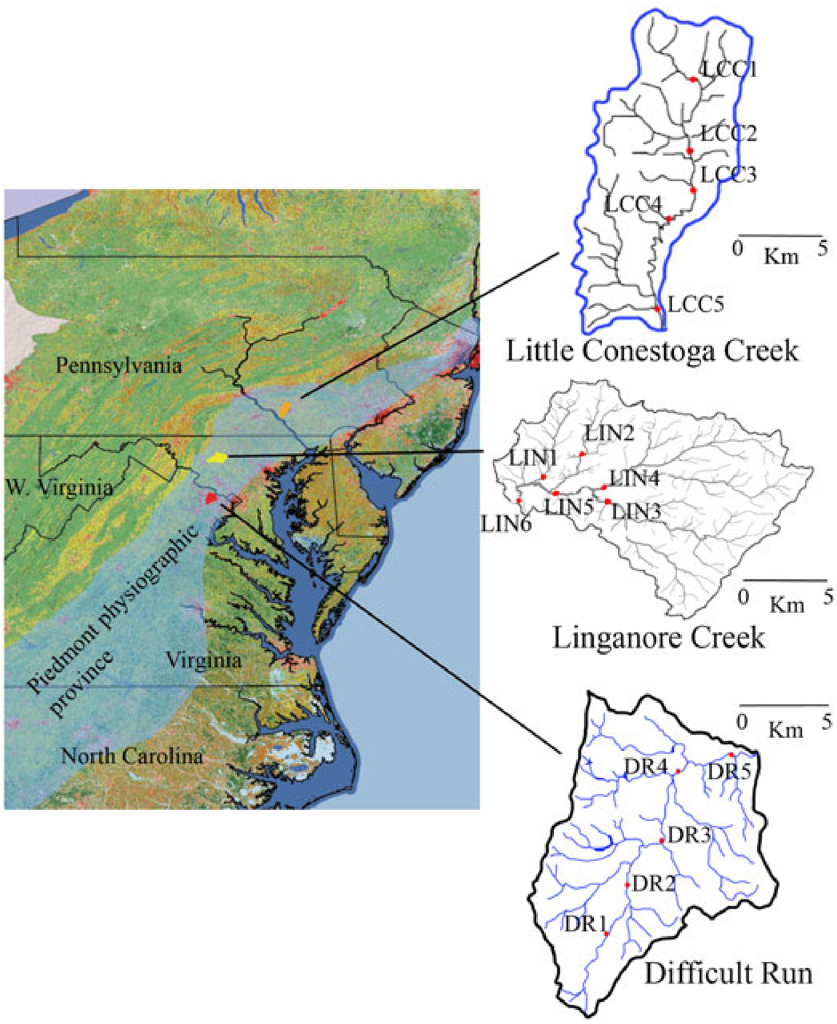

Figure 1. Map of the three study streams including individual sites. The Piedmont Physiographic Province is also delineated.

in order to determine contemporary stream processes. Stream sediment yields (g/m^2/yr) were compared with sediment budgets to calculate a floodplain trapping factor to determine floodplain ecosystem function, important for stream sediment and nutrient abatement (Noe and Hupp, 2009). The floodplain trapping factor is a unitless measure of the relative sediment trapping function of a floodplain at a site scale. The sediment budget and floodplain trapping factor should be useful for a greater understanding of stream sediment processes, and the targeting of floodplain or channel restoration, management, and future study.

Study Area

We intensely monitored three Piedmont tributaries to the Chesapeake Bay (Figure 1). All three had relatively similar watersheds in term of basin area and mean annual discharge (Table I). Each stream exhibits legacy sedimentation with 1–2 m of floodplain aggradation caused by colonial-era land clearing and mill pond deposition (Walter and Merritts, 2008; Schenk and Hupp, 2009). Floodplains exhibit a relatively homogenous layer of fine grained legacy sediment as potential stream inputs through lateral erosion (channel migration through bank erosion). Legacy sediment typically represents the upper 60 to 80% of any exposed bank and is primarily composed of silt and clay as opposed to pre-colonial sediments that are typically gleyed with a loamy texture (Hupp *et al.*, in press). Contrasting land use among basins provides an opportunity to contrast anthropogenic influences on sediment dynamics (Table I).

Little Conestoga Creek

The Little Conestoga Creek (LCC) drains predominately fractured carbonate bedrock (limestone, dolostone, and small amounts of shale) in southeast Pennsylvania (Berg and Dodge, 1981; Loper and Davis, 1998). The streambed consists primarily of fine sand in the upstream section of our study reach coarsening to gravel in the downstream sections. The LCC is a tributary of the Conestoga River, which drains into the Susquehanna River, the largest river by discharge to the Chesapeake Bay. The LCC is an urbanizing watershed with a mixture of agriculture and developed land (Table I). Row crop agriculture (13% of land area) was the dominate source of fine-grained (< 63 µm fluvial sediment, contributing 77% for 12 sampled storm events with streambanks contributing the other 23% (Gellis *et al.*, 2009). The riparian zone consists of scattered woodlands, manicured lawns, and old fields.

A USGS streamgage (site number: 01576712) operated on the LCC immediately downstream of Site 4 (river km 15.5, Figure 1) has a recorded mean discharge of 2.04, 1.54, and 1.59 m^3/s (71.9, 54.5, and 56.1 ft^3/s) for calendar years 2004, 2005, and 2006, respectively. Annual precipitation measured at Millersville, Pennsylvania was 108.1, 98.7, and 123.0 cm in 2004, 2005, and 2006, respectively. The mean precipitation from 1914 through 2007 was 104.3 cm/yr.

The LCC has been impacted over the last 150 years by the construction of numerous mill dams in conjunction with colonial-era land clearing and agriculture. Mill dams along the LCC are currently in various stages of function with the only fully intact dam consisting of a 3 m high run-of-river dam downstream of the USGS streamgage (Dorothy Merritts, pers. commun.; Pennsylvania Fish and Boat Commission, 2007).

Linganore Creek

Linganore Creek (LIN) drains a mix of sedimentary (siltstone) and metamorphic rock (quartzite) in south central Maryland (Reger and Cleaves, 2008). LIN has the highest percentage of agricultural land of the three watersheds (Table I). While the creek also had several mill dams in the past, none are currently present within the area of study. The creek drains to the Monocacy River, a tributary to the Potomac River which is the second largest river by discharge to the Chesapeake Bay. The riparian zone is occasionally forested with many reaches in active use for row crops or pasture. One USGS streamgage (01576712) operated on the LIN at the most downstream study site (LIN6) with mean discharge of 1.23, 1.74, and 1.68 m^3/s (43.6, 61.5, and 59.4 ft^3/s) for calendar years 2008, 2009, and 2010, respectively. Streamflow was measured beginning on July 17, 2008, providing a partial record for calendar year 2008. Annual precipitation measured at Frederick, MD was 113.8, 116.1, and 89.3 cm in 2008, 2009, and 2010, respectively. The mean annual precipitation from 1950 through 2010 was 100.9 cm.

Difficult Run

Difficult Run (DR) drains to the Potomac River in northern Virginia. The watershed is composed largely of metamorphic rocks (quartz rich schist, mica gneiss, metagraywacke; Southworth and Fingeret, 2000). DR has experienced land clearing, followed by use as pasture and dairy farms up until the middle of the 20th century. The watershed urbanized rapidly beginning around 1965 and extending into the 1990s. The majority of the watershed is low-density suburban housing and most of the floodplain is preserved as second-growth forest. DR previously had several low-head mill dams, none of which currently exist (Hupp *et al.*, in press). Grade control still exists locally due to culverts, pipe crossings, and areas of channel armoring (mostly rip-rap).

Two USGS streamgages operate on DR. The downstream streamgage (01646000) monitors the majority of the watershed (located at DR5, Figure 1). Mean discharge was 1.98, 2.20, and 1.73 m^3/s (69.9, 77.7, 61.2 ft^3/s) for calendar years 2008, 2009, and 2010, respectively. Annual precipitation, measured

Table I. Watershed characteristics of each stream studied. Sediment yield measurements from each stream are from their respective USGS streamgages except DR where an upstream streamgage collected sediment loads (USGS streamgage 01645704). Sediment loads were collected during water years 2008–2011, 2003, and 2009 for LIN, LCC, and DR, respectively

Stream	USGS streamgage	Annual mean discharge m^3/s (cfs)	Annual sediment yield Mg/km^2/yr	Basin Area Km^2	Land Use (%) Agriculture	Forested	Developed
Linganore Creek (LIN)	01642438	1.4 (50)	43.5	147	71	22	7
Little Conestoga Creek (LCC)	01576712	1.7 (61)	65.1	160	68	10	22
Difficult Run (DR)	01646000	1.8 (62)	163.9	141	6	40	54

at Vienna, VA was 106.6, 115.4, and 98.22 cm in 2008, 2009, and 2010, respectively. The mean annual precipitation from 1943 through 2010 was 110.9 cm.

Methods

Intensive monitoring sites were selected for each stream based on longitudinal position on the stream channel, the location of pre-existing geomorphic studies, and land access. Floodplain transects were established perpendicular to the channel extending from the top of the bank to the valley slope. Bank erosion transects corresponded with floodplain transects and extended from the top of bank to the top of the corresponding bank. Additional intermediate bank erosion transects were placed equidistant between floodplain transects at DR (Table II). Study reaches ranged from 100 to 200 m (Table III).

Field measurements included channel and floodplain surveys along transects at each site and documentation of bank height, channel width, floodplain width, and changes in channel morphology. Rod and optical level surveys were completed and referenced to temporary benchmarks for each transect. Floodplain transects consisted of monumented and surveyed lines with measurement stations for floodplain sedimentation measurements using feldspar claypad marker horizons located on the levee, backswamp, and occasionally the valley slope. Feldspar clay acts as an artificial marker that can be easily identified when measuring new sediment deposited over the clay (Baumann *et al.*, 1984; Hupp and Bazemore, 1993; Schenk *et al.*, 2011). Each transect had 1 to 13 claypad stations depending on the length of transect and the complexity of the geomorphic surface. Geomorphic surfaces (active margin, levee, and backswamp) were delineated using survey results. Active channel margins were defined as depositional benches within the channel (Osterkamp and Hupp, 1984). Levees, when present, were adjacent to the channel and clearly higher in elevation and drier than the backswamp; both levees and backswamps are components of the floodplain. Floodplain deposition rates were calculated using the mean deposition rate from each floodplain geomorphic surface weighted by the proportion of the entire floodplain each geomorphic unit occupies. Catchment area above each study site, elevation, gradient, width–depth ratio, and sinuosity along the reach at each site were determined from LiDAR imagery (0.03 m vertical accuracy), digital elevation models (DEMs), topographic maps, and channel cross-sections (USGS seamless data server: seamless.usgs.gov; Lancaster County, 2007). Relationships between fluvial geomorphic variables and both floodplain deposition and bank erosion were tested for significant correlations using Pearson Product-Moments analysis. Within each watershed, site floodplain deposition and bank erosion rates were related to basin area, channel sinuosity, channel gradient, bank height, channel cross-sectional area, and the ratios of bank height to floodplain width, channel width to depth, channel cross-sectional area to floodplain width and channel width to floodplain width. Variables were transformed when necessary to meet the parametric assumptions of the analyses.

Sediment density, percentage organic fraction (loss on ignition method), and sediment size were measured annually at feldspar claypad stations. The organic content of the top 5 cm of floodplain sediment was determined using loss on ignition (LOI) at 400°C for 16 h (Nelson and Sommers, 1996). Soil bulk density was measured to a depth of 2 cm to determine the sediment mass eroded or deposited; the methods are outlined in the US Department of Agriculture's Soil Survey Manual (Burt, 2004). Sediment particle size was determined by grinding a known amount of oven dried sediment with a mortar and pestle and then passing the sediment through a sonic sieve for 12 min. Sediment size is reported as a weight fraction with sediment divided into categories of greater than 0.5 mm (coarse sand), between 0.25 and 0.5 mm (sand), 0.125 and 0.24 mm (fine sand), 0.063 and 0.124 mm (very fine sand), and less than 0.063 (silt and clay). An inverse phi index was used to classify the soil texture for each site (Krumbein, 1936; Schenk and Hupp, 2009). The index multiplies the size proportion by the inverse of its phi unit (coarse sand fraction is multiplied by five, sand by four, fine sand by three, very fine sand by two, and silt and clay by one); resulting in a simple intuitive quantitative measure of soil texture; the index value increases with increasing grain size.

Table II. Study sites, number of transects, floodplain claypads (floodplain stations), bank erosion pins (bank stations), and dates of study by stream. Stream km at LIN is complicated due to LIN 1, 2, and 4 being on tributaries (Town Creek, Dollyhyde Creek, and North Fork, respectively). Station numbering is ordered according to increasing basin area

	Basin area (km^2)	Stream km	Period of record	Floodplain transects	Bank transects	Floodplain stations	Bank stations
Difficult Run (DR)							
DR1	14.3	21	June, 2008 - Dec. 2010	3	5	12	32
DR2	27.7	17.5	June, 2008 - Dec. 2010	4	7	12	42
DR3	73.9	12	June, 2008 - Dec. 2010	3	5	22	30
DR4	117.0	6.5	June, 2008 - Dec. 2010	3	3	20	16
DR5	141.3	2	Aug. 2008 - Dec. 2010	3	5	27	30
Little Conestoga Creek (LCC)							
LCC1	18.8	26.1	July, 2004 - June, 2007	2	2	7	9
LCC2	80.5	20.3	July, 2004 - June, 2007	2	2	4	8
LCC3	103.4	16.1	July, 2004 - June, 2007	2	2	3	8
LCC4	109.0	12.5	July, 2004 - June, 2007	2	2	11	7
LCC5	159.7	1.7	July, 2004 - June, 2007	2	2	4	7
Linganore Creek (LIN)							
LIN1	11.2	8.5	Aug. 2008 - Oct. 2010	3	3	15	9
LIN2	15.8	12.6	Sept. 2008 - Oct. 2010	3	3	15	18
LIN3	46.6	13.8	Sept. 2008 - Oct. 2010	3	3	16	20
LIN4	52.1	12.8	Aug. 2008 - Oct. 2010	3	3	13	12
LIN5	108.0	9.3	Aug. 2008 - Oct. 2010	3	3	11	11
LIN6	146.6	4.9	Aug. 2008 - Oct. 2010	3	3	10	9

Table III. Bank characteristics and erosion rates by study site, standard deviations are presented in parenthesis after mean values

	Basin area (km2)	Stream km	Bank height (m)	Bank height measurements	Reach length (m)	Bank erosion rate (mm/yr)	Bank measurements	Percent organic	Organic measurements	Bulk density (g/cm3)	Density measurements
Difficult Run (DR)											
DR1	14.3	21	2.0 (0.2)	6	150	-135 (130)	32	3.5 (1.6)	3	0.9 (0.0)	3
DR2	27.7	17.5	1.9 (0.1)	8	200	-75 (61)	42	3.1 (0.5)	3	1.0 (0.2)	3
DR3	73.9	12	2.3 (0.1)	6	125	-18 (32)	30	2.4 (0.5)	3	1.0 (0.1)	3
DR4	117.0	6.5	2.6 (0.1)	6	160	14 (64)	16	2.6 (0.1)	3	0.9 (0.2)	3
DR5	141.3	2	2.2 (0.2)	6	125	-55 (230)	30	1.1 (0.0)	3	1.5 (0.2)	3
Little Conestoga Creek (LCC)											
LCC1	18.8	26.1	0.8 (0.1)	4	150	-71 (99)	9	4.0 (0.8)	7	0.8 (0.1)	3
LCC2	80.5	20.3	1.3 (0.2)	4	150	-84 (55)	8	3.5 (2.9)	3	1.0 (0.3)	3
LCC3	103.4	16.1	1.4 (0.3)	4	150	-29 (27)	8	3.9 (0.6)	8	1.0 (0.1)	3
LCC4	109.0	12.5	1.5 (0.3)	4	150	-163 (182)	7	4.2 (1.0)	7	1.1 (0.2)	3
LCC5	159.7	1.7	1.9 (0.8)	4	150	-94 (98)	7	4.1 (0.8)	4	1.0 (0.3)	3
Linganore Creek (LIN)											
LIN1	11.2	8.5	1.0 (0.3)	6	140	-15 (42)	9	3.7 (0.4)	3	1.4 (0.1)	3
LIN2	15.8	12.6	1.1 (0.1)	4	170	-33 (59)	18	3.1 (0.2)	3	1.5 (0.1)	3
LIN3	46.6	13.8	1.3 (0.2)	4	120	-64 (75)	20	4.0 (0.4)	3	1.4 (0.2)	3
LIN4	52.1	12.8	1.1 (0.3)	6	200	-73 (99)	12	3.8 (0.2)	3	1.5 (0.1)	3
LIN5	108.0	9.3	1.5 (0.3)	6	150	-107 (90)	11	5.5 (2.5)	3	1.1 (0.2)	3
LIN6	146.6	4.9	1.7 (0.9)	6	100	-46 (57)	9	5.5 (0.2)	3	1.3 (0.2)	3

Bank erosion transects consisted of 3 to 9 erosion pins (1 m long steel rods) installed normal to the ground profile along the bank face (Figure 2). Pin exposure was measured annually and after significant flood events. Exposed pins (greater than 20 cm of erosion) were reset to the bank surface during each field visit. Sediment samples were collected along the bank for sediment density, organic content, and sediment texture.

Sedimentation rates at each site were calculated by dividing total accretion over a claypad by time between installation and the final measurement. Values were normalized by floodplain area and presented as sedimentation in g/m^2/yr. The mass of sediment flux (deposition or erosion) was determined by the depth of clay pad burial or bank pin exposure, the bulk density of sediment, the assumption that the clay pad, or bank pin, represents the square meter around it, and the date between measurements and the installation period.

$$\varphi = (d \times \rho \times 1000)/t \tag{1}$$

where φ = sedimentation rate (floodplain claypads, g/m^2/yr) or erosion rate (bank pins, g/m^2/yr), d = claypad burial (mm) or bank pin exposure (mm), ρ = bulk density (g/cm^3), and t = time (yr).

Bank erosion rates were organized by site location and are presented similar to floodplain sedimentation (Equation (1)) using bank pin exposure (mm) instead of floodplain pad burial. A site sediment budget, per meter of longitudinal stream, was estimated using the bank height, floodplain width, and study reach length. This sediment budget does not include channel bed aggradation/degradation and does not account for bank pins and clay pads that were lost to excessive erosion or deposition (< 20% of pins or pads lost per stream). Site floodplain sedimentation was calculated using Equation (2), bank erosion using Equation (3), and net sediment budget using Equation (4). Floodplain width was divided into active margin, levee, and backswamp geomorphic units, as appropriate, and the deposition rate was calculated using the proportional deposition rate from each of those geomorphic units.

$$\psi_f = \varphi_f \times w_f \tag{2}$$

where ψ_f = site floodplain sedimentation (g/m/yr), φ_f = sedimentation rate (g/m^2/yr), and w_f = floodplain width (m).

$$\psi_b = \varphi_b \times h_b \tag{3}$$

where ψ_b = site bank erosion (g/m/yr), φ_b = bank erosion rate (g/m^2/yr), and h_b = mean bank height (m).

$$\psi = \psi_f - \psi_b \tag{4}$$

where ψ = net site sediment budget (g/m/yr, positive is aggradational, negative is erosional), ψ_f = site floodplain sedimentation (g/m/yr), and ψ_b = site bank erosion (g/m/yr).

Calculating the floodplain trapping factor – a new index for assessing floodplain ecosystem function (nutrient and sediment retention)

A gross and net floodplain trapping factor was estimated to provide a comparable measure of sediment trapping between each stream. The trapping factor was calculated by taking the individual site deposition (Equation (2), g/m/yr) and adjusting for that site's area (reach length multiplied by floodplain width). This was done for both gross deposition (floodplain deposition only, Equation 5(a)) and net deposition (floodplain deposition minus bank erosion, Equation 5(b)).

$$tr_g = [(\psi_f \times l)/a]/SY \quad \text{(gross floodplain trapping factor)} \tag{5a}$$

$$tr_n = [(\psi \times l)/a]/SY \quad \text{(net floodplain trapping factor)} \tag{5b}$$

where tr_g = gross floodplain trapping factor, tr_n = net floodplain trapping factor, ψ_f = site floodplain sedimentation (g/m/yr), ψ = net site sediment budget (g/m/yr), l = reach length (m), a = site area (m^2), and SY = stream sediment yield (g/m^2/yr).

The resulting floodplain sedimentation yield (g/m^2 of floodplain/yr) was then divided by the appropriate stream sediment yield (g/m^2 of basin/yr, Table I) to provide both a gross and net floodplain trapping factor at each site. The measurement is unitless and provides the relative floodplain sediment trapping for a given area of floodplain. For example, a gross trapping factor of 20 would indicate that a given area of floodplain would trap the equivalent of 20 times the same area of upland sediment sources. A net trapping factor of 20 would indicate that a given area of floodplain, corrected for bank erosion, would trap the equivalent of 20 times the same area of upland sediment sources.

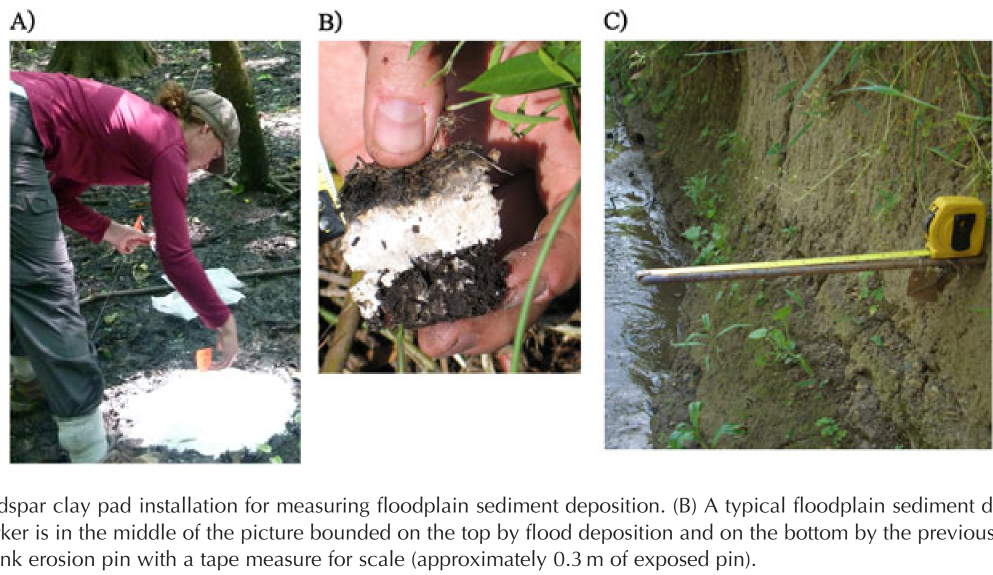

Figure 2. (A) Feldspar clay pad installation for measuring floodplain sediment deposition. (B) A typical floodplain sediment deposition core. The white feldspar marker is in the middle of the picture bounded on the top by flood deposition and on the bottom by the previous floodplain surface. (C) An exposed bank erosion pin with a tape measure for scale (approximately 0.3 m of exposed pin).

Results

Bank erosion rates

Gross bank erosion rates, bulk density, percentage organic content, reach length, and bank height are presented in Table III. Mineral and organic erosion was separated to determine the contribution of each to the sediment supply. Banks were net erosional, except at DR4, and the eroded material consists mostly of mineral sediment (94.5% or higher).

Floodplain deposition rates, sediment grain size, and the floodplain trapping factor

Gross floodplain deposition rates, bulk density and percentage organic content for each geomorphic zone are presented in Table IV. Mineral and organic sediment were separated to determine the components of sediment storage on the floodplain at each site. Floodplain characteristics for each site are included in Table V. Backswamps and banks largely consisted of silts and clays (<63 μm), while levees occasionally had lenses of very fine to fine sands from large floods. Further information on grain size distribution is available in Schenk and Hupp (2009) and Hupp *et al*. (in press). The mean gross floodplain trapping factor was 29, 68, and 107 for DR, LCC, and LIN, respectively. The mean net floodplain trapping factor was 18, –14, and 46 for DR, LCC, and LIN, respectively.

Channel and floodplain morphology

Relevant channel characteristics are provided in Table VI. Difficult Run and Linganore Creek flow freely throughout the study site, Little Conestoga Creek, however, has a low-head dam between LCC4 and LCC5 and an actively migrating knickpoint downstream of LCC1 (Schenk and Hupp, 2009). Linganore sites LIN1, 2, and 4 are tributaries of the main channel and the channel at LIN6 is bounded on the outside bend by a bedrock cliff.

Within DR, the ratio of channel to floodplain width best explained bank erosion rate, bank erosion, floodplain deposition rate, and floodplain deposition (Pearson Product-Moment correlation: $n = 5$, $r < –0.824$, $P < 0.086$). Channel:floodplain width also was strongly negatively correlated with the overall site budget, however, gradient was a slightly better predictor ($r = –0.946$ versus –0.877 for gradient and channel:floodplain width, respectively). Within LIN, bank erosion rate was best explained by the ratio of channel width to depth ($n = 6$; $r = –0.912$, $P = 0.011$) whereas bank erosion was best explained by channel width (n = 6; r = –0.954, $P = 0.003$). Floodplain deposition rate was best explained by channel gradient ($r = –0.836$, $P = 0.038$) but floodplain deposition was not predictable ($P > 0.146$). LIN site budgets were best correlated with channel cross-sectional area:floodplain width ($r = –0.800$, $P = 0.056$). At LCC, bank erosion rate was best explained by channel sinuosity ($n = 5$, $r = –0.834$, $P = 0.079$) but bank erosion was not explained ($P > 0.186$). Floodplain deposition rate and floodplain deposition were best correlated with channel width:depth ($r = 0.865$, $P = 0.058$; and $r = 0.937$, $P = 0.019$, respectively). LCC site budgets were best explained by floodplain width (r = 0.986, $P = 0.002$).

Sediment budgets and Pearson product-moment correlation results

The results from using Equation (2) and (3) are presented in Table VII. When data from all three rivers are evaluated simultaneously, the ratio of bank height to floodplain width best explains the net site sediment budget (kg/m/yr; $n = 16$, $r = –0.783$, $P = <0.001$) indicating that a site becomes more erosional (or less depositional) as the bank height increases relative to the floodplain width. Bank height, at least at DR, appears to be unrelated to current and historic dam locations (Hupp *et al*., in press). Site floodplain deposition load was best explained by channel cross-sectional area (kg/m/yr; $r = 0.660$, $P = 0.005$) and nearly as well explained by the ratio of bank height to floodplain width ($r = -0.654$, $P = 0.006$). Site floodplain deposition rate was best explained by channel W:D (g/m^2/yr; $r = 0.672$, $P = 0.004$) while bank erosion rate was best explained by the ratio of channel width to floodplain width (g/m^2/yr; $r = –0.541$, $P = 0.031$). Site bank erosion was best correlated with the ratio of channel cross-sectional area to floodplain width (kg/m/yr; $r = –0.558$, $P = 0.025$). Basin area, channel sinuosity, and stream gradient were not correlated with any geomorphic rate measurements ($P > 0.101$).

Discussion

The bank–floodplain sediment budget approach to basin sediment dynamics is a simple and relatively inexpensive means to assess processes and trends in channel stability and sediment dynamics. This case study of Piedmont streams allows observation of the impact of historical and modern land use. There are over 15 million people in the Bay watershed including several large metropolitan areas; the impacts of urbanization (flashier streams) are probably a significant variable in the delivery of sediment to the Bay (Booth, 1990; Booth *et al*., 2002; Phillips, 2002). We observe the effect of urbanization at DR, a 'flashy' stream due to impervious cover, where the upstream erosion leads to more than double the amount of sediment storage downstream, compared with the other study streams (Figure 3, Table IV).

We also observe ongoing disturbance along the LCC channel due to historical dams and a remaining low-head dam. The bank–floodplain sediment budget provides a method to quantitatively assess and monitor systems that are out of dynamic equilibrium, such as LCC (Schenk and Hupp, 2009). Streams adjusting to disturbance follow a usually predictable trajectory towards dynamic channel equilibrium (Schumm and Parker, 1973) though often the new channel equilibrium is different from pre-disturbance (Simon and Hupp, 1992). Finally, this budget reveals the effects of historical and geographic contingency. Contingency, the concept that current conditions for any particular stream are caused by a unique mix of geomorphic drivers and controls (Phillips, 2007), appears to be relevant for the study of these three streams.

Little Conestoga Creek (LCC)

The effect of human alterations is greatest at LCC (current dam, channel incision with an active knickpoint; Schenk and Hupp, 2009) complicating the relationship between fluvial geomorphic parameters and sediment trends at a site scale. The existing dam is between LCC4 and 5 while the active knickpoint (causing channel incision) is between LCC1 and 2 (Schenk and Hupp, 2009). Both disturbances are noticeable in the channel W:D of nearby sites (Table VI). Not surprisingly the site deposition rate and load increases significantly with a greater channel W:D ($P = 0.058$ and 0.019, respectively). The greater floodplain rate with a relatively shallow channel (large W:D) indicates the increased floodplain connectivity with decreased relative bank height at LCC. This trend (increased W:D leads to

Table IV. Floodplain deposition rates and characteristics by study site including standard deviations (STDEV)

	Basin area (km2)	Stream km	Active margin	Levee	Backswamp	Rate STDEV	Active margin	Levee	Backswamp	Organic STDEV	Active margin	Levee	Backswamp	Density STDEV
			Deposition rate (mm/yr)				Percent organic content				Bulk density (g/cm3)			
Difficult Run (DR)														
DR1	14.3	21	N/A	5.5	1.3	5.2	N/A	7.1	7.9	1.1	N/A	0.8	0.8	0.1
DR2	27.7	17.5	N/A	4.5	2.6	0.8	N/A	1.0	11.2	1.7	N/A	1.1	0.6	0.2
DR3	73.9	12	N/A	9.1	10.7	6.7	N/A	5.9	7.6	1.3	N/A	0.7	0.7	0.1
DR4	117.0	6.5	N/A	20.9	6.9	11.2	N/A	1.1	10.8	1.5	N/A	1.1	0.4	0.1
DR5	141.3	2	N/A	7.8	3.8	7.8	N/A	0.6	6.2	0.8	N/A	1.2	0.7	0.1
Little Conestoga Creek (LCC)														
LCC1	18.8	26.1	N/A	-5.7	-4.1	3.2	N/A	4.0		0.8	N/A	0.8		0.1
LCC2	80.5	20.3	N/A	16.4	9.1	5.4	N/A	3.5		2.9	N/A	1.0		0.3
LCC3	103.4	16.1	N/A	2.7	0.6	1.3	N/A	3.9		0.6	N/A	1.0		0.1
LCC4	109.0	12.5	N/A	7.7	11.5	9.6	N/A	4.2		1.0	N/A	1.1		0.2
LCC5	159.7	1.7	N/A	0.6	5.3	2.8	N/A	4.1		0.8	N/A	1.0		0.3
Linganore Creek (LIN)														
LIN1	11.2	8.5	No data	N/A	4.8	8.2	N/A	N/A	8.9	1.8	N/A	N/A	1.2	0.0
LIN2	15.8	12.6	N/A	N/A	3.3	5.8	N/A	N/A	9.1	2.0	N/A	N/A	0.9	0.1
LIN3	46.6	13.8	29.0	2.4	3.6	14.0	5.4	N/A	9.8	4.3	1.0	N/A	1.1	0.1
LIN4	52.1	12.8	28.1	N/A	0.3	13.2	2.1	N/A	8.3	0.8	1.4	N/A	1.1	0.1
LIN5	108.0	9.3	24.2	N/A	1.8	11.3	6.2	N/A	6.2	1.1	1.2	N/A	1.3	0.1
LIN6	146.6	4.9	N/A	N/A	2.7	6.4	N/A	N/A	7.9	0.8	N/A	N/A	1.1	0.0

Table V. Floodplain widths (separated into active margin, levee, and backswamp) and study site length by site. Standard deviations for each mean value are presented in parenthesis; 'n/a' represents means derived from two measurements and do not have a standard deviation

	Basin area (km2)	Stream km	Active margin width (m)	Levee width (m)	Backswamp width (m)	Transects n	Reach length (m)
Difficult Run (DR)							
DR1	14.3	21	0	18 (11)	31 (7)	3	150
DR2	27.7	17.5	0	35 (23)	22 (17)	4	200
DR3	73.9	12	0	47 (26)	98 (53)	3	125
DR4	117.0	6.5	0	28 (2)	134 (39)	3	160
DR5	141.3	2	0	15 (33)	123 (85)	3	125
Little Conestoga Creek (LCC)							
LCC1	18.8	26.1	0	5 (5)	13 (4)	3	150
LCC2	80.5	20.3	0	5 (7)	39 (20)	3	150
LCC3	103.4	16.1	0	8 (5)	18 (7)	3	150
LCC4	109.0	12.5	0	9 (6)	20 (4)	3	150
LCC5	159.7	1.7	0	9 (5)	9 (5)	3	150
Linganore Creek (LIN)							
LIN1	11.2	8.5	4 (n/a)	0	55 (5)	3	140
LIN2	15.8	12.6	0	0	23 (0.1)	3	170
LIN3	46.6	13.8	7 (n/a)	2 (n/a)	25 (10.8)	3	120
LIN4	52.1	12.8	6 (n/a)	0	73 (8)	3	200
LIN5	108.0	9.3	3 (n/a)	0	27 (24)	3	150
LIN6	146.6	4.9	0	0	49 (14)	3	100

Table VI. Channel and floodplain dimensions by site

	Sinuosity	Channel gradient	Channel Width (m)	Channel Depth (m)	Channel W:D	Floodplain width (m)
Difficult Run (DR)						
DR1	1.38	0.0050	11	1.9	5.8	49
DR2	1.22	0.0025	13	1.8	7.0	57
DR3	1.48	0.0018	16	2.0	7.8	145
DR4	1.57	0.0019	19	3.1	6.1	162
DR5	1.44	0.0019	25	2.5	9.9	138
Little Conestoga Creek (LCC)						
LCC1	1.09	0.0017	3	0.8	4.1	18
LCC2	1.08	0.0049	13	1.3	9.9	44
LCC3	1.04	0.0071	13	1.4	8.7	26
LCC4	1.53	0.0023	15	1.5	9.7	28
LCC5	1.01	0.0129	15	1.9	7.5	18
Linganor Creek (LIN)						
LIN1	1.11	0.0128	7	1.0	7.3	59
LIN2	1.28	0.0048	10	1.1	8.8	23
LIN3	1.10	0.0024	15	1.3	11.6	33
LIN4	1.28	0.0018	12	1.1	11.3	79
LIN5	1.24	0.0024	22	1.5	14.8	30
LIN6	195	0.0150	14	1.7	8.2	49

increased floodplain deposition) probably holds true for many stream systems in the mid-Atlantic region, though there may be exceptions where the channel cross-sectional area is driven solely by sediment loss creating a system where channel capacity exceeds most floods.

Sinuosity was the explanatory variable for site erosion rates ($P = 0.079$) where sites with lower sinuosity experienced high erosion rates. The site sediment budget was not predicted by gradient, sinuosity, or W:D but by floodplain width ($P = 0.002$). Greater floodplain widths at a site corresponds to greater net site sediment budgets (floodplain sedimentation > bank erosion). This has been observed previously in Wisconsin and Illinois where relatively large floodplains trapped more sediment per area than narrow floodplains (Magilligan, 1985). Narrow floodplains, due usually to geologic constraints, tend to have deeper channels (lower W:D) to transport water and sediment rapidly through the constrained reach (Magilligan, 1985). A relatively wide floodplain would also decrease flood velocities more than a narrow floodplain allowing for greater sedimentation.

Linganore Creek (LIN)

The results at LIN probably represent trends and processes of a typical Piedmont agricultural stream. Bank erosion rates decrease with a higher W:D value while the floodplain deposition intensity shows an inverse trend. This indicates that there is a general trend of increasing floodplain deposition intensity (and decreasing bank erosion intensity) with a relatively shallow channel. The floodplain deposition rate was best explained by gradient, with lower gradient increasing deposition on the floodplain. This is probably usual for relatively undeveloped

Table VII. Erosion values from bank pin measurements and deposition from floodplain clay pads by site. Negative numbers indicate erosion, positive numbers indicate accretion. Standard deviations are provided, when available, in parentheses. The standard deviation is a product of the variability in measurements of bank height, floodplain width, deposition and erosion rates, organic content, and soil bulk density (see previous tables for individual variable standard deviations). Standard deviations were not computed for LIN due to the unknown variability in floodplain widths at that stream (see Table V).

	Basin area (km^2)	Stream km	Mineral erosion (Kg/m/yr)	Organic erosion (Kg/m/yr)	Total erosion (Kg/m/yr)	Active margin	Levee	Backswamp	Active margin	Levee	Backswamp	Total deposition (Kg/m/yr)	Site sediment budget (Kg/m/yr)
						Mineral deposition (Kg/m/yr)			Organic deposition (Kg/m/yr)				
Difficult Run (DR)													
DR1	14.3	21	238 (235)	-9 (9)	**-246 (235)**	N/A	72 (91)	29 (130)	N/A	6 (6)	3 (10)	**110 (159)**	**-136 (284)**
DR2	27.7	17.5	-128 (120)	-4 (4)	**-132 (119)**	N/A	169 (312)	30 (30)	N/A	2 (3)	4 (3)	**204 (314)**	**72 (336)**
DR3	73.9	12	-40 (74)	-1 (2)	**-41 (74)**	N/A	286 (291)	725 (671)	N/A	18 (17)	60 (51)	**1088 (733)**	**1047 (738)**
DR4	117.0	6.5	31 (150)	1 (4)	**32 (150)**	N/A	656 (958)	358 (671)	N/A	7 (11)	44 (73)	**1065 (1173)**	**1097 (1182)**
DR5	141.3	2	-179 (760)	-2 (8)	**-181 (760)**	N/A	140 (396)	325 (757)	N/A	1 (2)	21 (47)	**510 (487)**	**307 (306)**
Little Conestoga Creek (LCC)													
LCC1	18.8	26.1	-42 (64)	-2 (3)	**-45 (64)**	N/A	-21 (26)	-39 (36)	N/A	-1 (1)	-2 (1)	**-63 (44)**	**-107 (78)**
LCC2	80.5	20.3	-110 (81)	-4 (4)	**-114 (80)**	N/A	89 (143)	350 (431)	N/A	3 (5)	13 (15)	**455 (455)**	**341 (462)**
LCC3	103.4	16.1	-41 (39)	-2 (2)	**-43 (39)**	N/A	23 (18)	10 (25)	N/A	1 (1)	0 (1)	**35 (31)**	**-8 (50)**
LCC4	109.0	12.5	-253 (310)	-11 (13)	**-265 (310)**	N/A	67 (106)	228 (221)	N/A	3 (4)	10 (9)	**308 (245)**	**43 (394)**
LCC5	159.7	1.7	-180 (208)	-8 (9)	**-187 (210)**	N/A	5 (26)	47 (41)	N/A	0 (1)	2 (2)	**54 (49)**	**-133 (213)**
Linganore Creek (LIN)													
LIN1	11.2	8.5	-21 (59)	-1 (2)	**-22 (59)**	No data	N/A	283	No data	N/A	28	**311**	**289**
LIN2	15.8	12.6	-52 (98)	-2 (3)	**-54 (98)**	N/A	N/A	63	N/A	N/A	6	**69**	**15**
LIN3	46.6	13.8	-112 (139)	-5 (6)	**-117 (138)**	184	4	90	0	0	10	**288**	**172**
LIN4	52.1	12.8	-112 (167)	-4 (6)	**-117 (167)**	223	N/A	23	0	N/A	2	**248**	**132**
LIN5	108.0	9.3	-169 (156)	-10 (10)	**-179 (156)**	80	N/A	58	0	N/A	4	**142**	**-37**
LIN6	146.6	4.9	-97 (138)	-6 (8)	**-103 (138)**	N/A	N/A	137	N/A	N/A	12	**148**	**45**

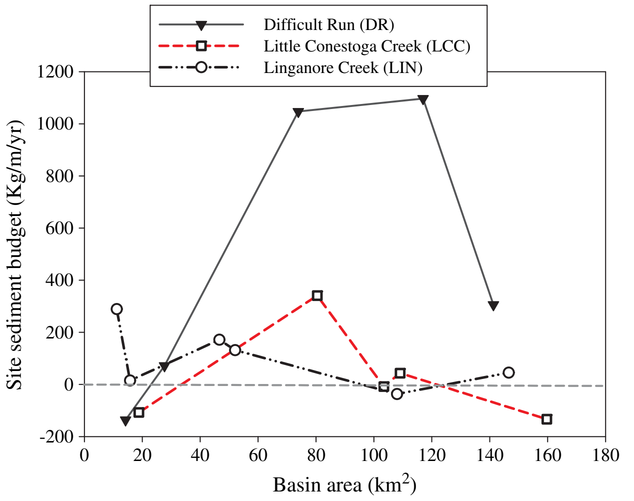

Figure 3. Site sediment budget in kg/yr per meter of longitudinal stream reach. Positive numbers denote net deposition.

watersheds that have not undergone the channel incision common with urbanization. Despite this trend, the overall site sediment budget becomes more erosional at LIN as the contributing basin area increases (Figure 5). The best explanatory variable for the site sediment budget was the ratio of channel cross-sectional area to floodplain width: the site became more net erosional as the relative area of the channel increased.

Difficult Run (DR)

Both bank erosion and floodplain deposition intensity increase with sinuosity at DR. This may indicate that floods are highly energetic, having a disproportionately higher impact on a sinuous reach than a straight reach. Banks on outside bends of a sinuous reach will erode faster with higher stream power (product of discharge and gradient), common in a 'flashy' system (Pizzuto *et al.*, 2000). The material from that bank can then be deposited on the nearby floodplain during a short-duration flood, also common in a 'flashy' system (Meade *et al.*, 1990; Hupp *et al.*, 2009). The sediment relationship with sinuosity at DR is not surprising given that DR is the most urbanized watershed of the three study streams and has had higher peak discharges and more peaks above base since urbanization (Hupp *et al.*, in press). Bank erosion and floodplain deposition rates were best explained by the channel to floodplain width ratio. The net site budget was also significantly correlated with the same ratio. The ratio provides a measure of the floodplain size relative to the size of the channel. A 100 m wide floodplain adjacent to a 100 m wide channel would therefore have a smaller ratio than a 100 m wide floodplain adjacent to a 10 m wide channel. Erosion and deposition load, and the net site sediment budget all increase as the relative floodplain width increases. The increase in deposition load as the relative floodplain width increases is intuitive; a greater floodplain area can trap more flood derived sediment than a small floodplain. The increase in erosion load is also intuitive; the ratio of channel width to floodplain width can also be interpreted as a measure of relative channel width. A relatively narrow channel (relatively large floodplain) could be more erosive due to channel confinement. A narrow channel would be more prone to erosion in a 'flashy' urban watershed, such as DR (Wolman, 1967, Nanson and Young, 1981).

Inter-stream comparisons

The majority of sites show net deposition of sediment with an increasing trend with basin area at DR, the opposite for LIN, and no trend at LCC (Figure 3). As shown in the preceding sections, each stream's sediment budget, bank erosion, and floodplain deposition is best explained by a different variable. This reinforces the idea of contingency and refutes the assertion that individual streams can be understood using a broad classification (Natural Channel Design – Rosgen, 1996; mill pond dam effects – Walter and Merritts, 2008). Physical laws and regional contingencies, do however, impact streams in predictable ways creating general stream patterns and processes (Phillips, 2006; Hupp and Rinaldi, 2007; Tetzlaff *et al.*, 2009).

Sediment budgets by site were compared using the relative floodplain area (ratio of the channel width to floodplain width) to determine whether a general process drives the budget. When compared all three streams show a linear trend towards higher net storage at sites with relatively large floodplains (Figure 4). Mean site bank erosion rates (g/m^2/yr) were then compared with relative floodplain area to discount the possibility that the trends in Figure 4 are an artefact of the site budget calculation (Equation (2), disproportionally large floodplains can have a disproportionally large impact on sediment budgets due to the calculation). The same general trends exist when comparing bank erosion rates with relative floodplain area (Figure 5) as observed when

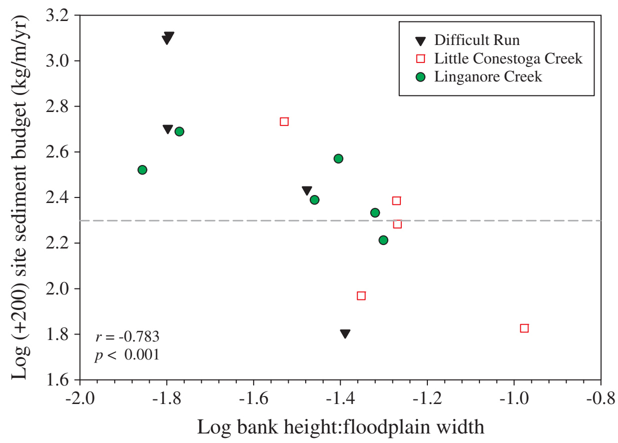

Figure 4. Site sediment budget (positive values denote net accretion) by the ratio of bank height to floodplain width. The dashed line represents a sediment budget of 0 kg/m/yr. The correlation ($r = -0.783$, $P < 0.001$) was conducted using a Pearce Product-Moment test.

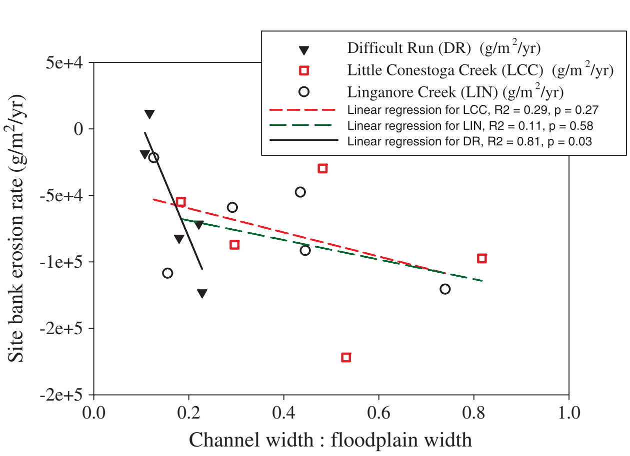

Figure 5. Site bank erosion compared with the ratio of the channel width to floodplain width. The higher the channel width:floodplain width value the smaller the floodplain relative to the channel.

comparing sediment budgets by site (Figure 4). The rate of bank retreat at each stream is correlated with the channel and floodplain geometry (areas with relatively small floodplains, or relatively wide channels, have accelerated bank retreat).

A comparison of all the streams shows that the site sediment budget decreased (less net storage) for each stream as the ratio of channel width to floodplain width increased (Figure 4). The larger the floodplain, relative to the channel, the greater the net retention of sediment. A commensurate drop in bank erosion intensity (rate) was found as the relative width of the floodplain increased (Figure 5). Bank erosion rates may increase as the relative size of the floodplain decreases due to the decreased proportion of flood flow that will travel through a relatively small floodplain. As the proportion of flood flow confined to the channel increases the stream power will increase. An increase in stream power relative to areas with larger floodplains during the same flood would probably lead to higher bank erosion (as shown by bank erosion rate in Figure 5). Gradient will also increase stream power but gradient was not identified as highly correlated for all three streams. Trends in both net site sediment budgets and bank erosion rates are best explained by a linear regression of relative floodplain size at both DR and LIN, but are poorly defined at LCC (Figure 4 and 5). The relation between geomorphic parameters and the sediment budget is strongest at the urbanized setting (DR) where the watershed land cover is relatively static on an annual scale. The relationship works in a relatively equilibrated agricultural system (LIN) but may not be as strong as with DR due to the complicating factor of seasonal land use (spring and summer active tilling for row crop agriculture and undisturbed fields in the winter at LIN versus consistent forest or manicured lawn use at DR). A tool is needed to better compare streams, preferably a metric that can be utilized for understanding geomorphic process, contingency, and also stream management.

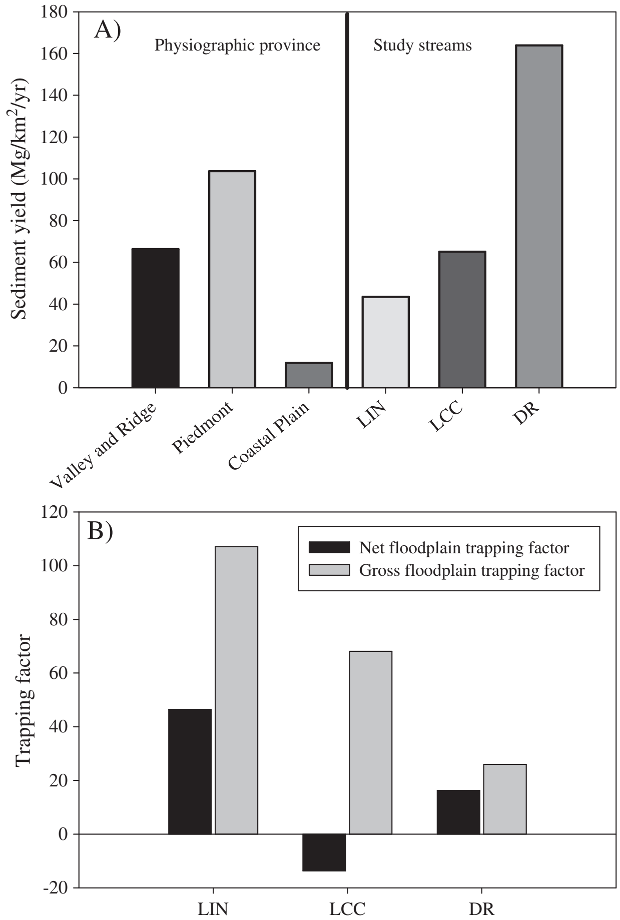

Figure 6. (A) Mean sediment yields for select physiographic provinces of the Chesapeake Bay (Gellis *et al.*, 2009) and sediment yields for the study stream from Table I. (B) Mean gross and net floodplain trapping factor by study stream. LIN, LCC, and DR represent Linganore Creek, Little Conestoga Creek, and Difficult Run, respectively.

The use of the floodplain trapping factor to determine stream function

Floodplains serve an ecosystem function as a sink for suspended sediment and associated stream nutrients (Noe and Hupp, 2009). Therefore, understanding how individual floodplains function as sediment sinks is important for management (Phillips, 2002), channel processes (Hupp and Rinaldi, 2007) and non-linear (Phillips, 2006) geomorphic interests. The downstream (DR3, 4, and 5) net site sediment budgets are an order of magnitude higher at DR than the other two streams (Figure 4) probably due to the urbanized nature of the watershed, which provides for high sediment loads that may be trapped on downstream floodplains. The sediment yield (163.9 Mg/km^2/yr) is also distinctly higher in DR than the other streams and higher than the mean sediment yield for Piedmont streams (103.7 Mg/km^2/yr; Figure 6(a); Gellis *et al.*, 2009). A better comparison of site sediment budgets between streams is the floodplain trapping factor, a measure that takes into account the range of sediment yields between streams. DR has the lowest floodplain trapping factor in terms of gross floodplain storage and the intermediate trapping factor when comparing net site sediment budgets. The low trapping factor may partly be due to the location of the sediment streamgage at DR. DR is the only stream of the three that has a sediment streamgage at the upstream boundary of the study area and not at the downstream boundary. The sediment yield is probably higher at the upstream site than at the downstream-most site due to the cumulative impact of floodplain trapping (Vente and Poesen, 2005). The upstream placement of the sediment streamgage probably contributes to a lower trapping factor. The difference between the sediment yield at DR1 and DR5 will not be known until the sediment streamgage at DR5 has operated for a sufficient period of time (sediment measurements began in spring 2012). The impact of urbanization on the sediment yield at DR should not, however, be understated. The sediment yield at LCC, which is still undergoing channel change from an existing dam and dam removals is only marginally higher than LIN and neither are similar to the sediment yield of DR.

The agricultural stream, LIN, has the most effective floodplains for trapping sediment and associated nutrients (107 gross floodplain trapping factor) while the stream in the greatest imbalance, LCC, has the least effective floodplains when you take into account associated bank erosion (–14 net floodplain trapping factor, Figure 6(b)). The gross trapping factor, therefore, is a measure of floodplain connectivity with the channel, and by extension, floodplain ecosystem service (sediment and nutrient trapping; Walling and Owens, 2003; Noe and Hupp, 2009). Net trapping factor allows for the comparison of sites between streams in terms of sediment balance. Negative net values represent sites or streams that are sources of sediment. Future research along other Piedmont streams may produce a large enough sample size to determine, from a stream restoration perspective, a threshold net trapping factor above which a site could be considered to be ‘functioning’ and below which, the site could be considered ‘impaired’. We are not aware of a similar tool that allows for a quick quantitative evaluation of floodplain sediment and nutrient ecosystem service (gross floodplain trapping factor) or channel sediment balance (net floodplain trapping factor).

Conclusion

We provide a bank and floodplain sediment budget for three Piedmont streams (LIN, agricultural; LCC, urbanizing; DR, urban-suburban) to rapidly assess streams for areas of sediment supply and storage. Net site sediment budgets (floodplain deposition flux minus bank erosion flux) were correlated against a suite of geomorphic parameters. Net site sediment budgets were best explained by gradient at DR, the relation of channel cross-sectional area to floodplain width at LIN, and floodplain width at LCC. All three streams had greater net site budgets (maximum = 1097, minimum = –136 kg/m/yr) as the relative floodplain increased (lower ratio of channel width to floodplain width) indicating that bank erosion decreases and floodplain deposition increases as relative floodplain width increases. We attribute the trends in bank erosion rates to a decrease in stream power at high flows as a large floodplain could absorb more of a flood's discharge than a smaller floodplain. The trend in both net site budget and bank erosion intensity was weakest at LCC where the channel is in disequilibrium (probably most among the three streams) due to an intact low-head dam and an unrelated migrating knickpoint (Schenk and Hupp, 2009). Despite the overall trends with relative floodplain size, no one geomorphic variable or suite of variables, explained erosion and deposition for all three streams. Historical and geographic contingency was demonstrated to a degree by the case study, requiring us to develop a new tool for comparing streams.

We created a geomorphic metric: the floodplain trapping factor, to compare site sediment trends between streams and for intra-stream analyses alike (Hupp *et al*., in press). Net site sediment budgets and site floodplain fluxes (mass of sediment/m of longitudinal stream/time) were normalized by reach length and divided by the stream's sediment yield (mass of sediment/watershed area/time) to provide a unitless measure of floodplain sediment trapping. Using this factor we determined that the agricultural stream (LIN) had the highest gross floodplain trapping efficiency (107) while the currently most impacted stream (LCC) had the lowest net floodplain trapping efficiency (–14). This new calculation, which we are calling the floodplain trapping factor, not only allows for a simple and intuitive measure of floodplain ecosystem function (Noe and Hupp, 2009) but should also be a useful tool for future studies and management actions in the Chesapeake Bay watershed and beyond.

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